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STRESS INTENSITY FACTOR AND LOAD-LINE DISPLACEMENT EXPRESSIONS FOR THE ROUND BAR BEND SPECIMEN

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New wide-range expressions for stress intensity factor and load-line displacement for three-point bend fracture tests with the round bar specimen are described.

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INTRODUCTION

In prior work (ref 1) an expression was developed for calculating the stress intensity factor, K, for a straight-fronted edge crack of any depth in a round bar loaded in three-point bending. The expression was based on experimental compliance results of Bush (ref 2), finite element results of Daoud and Cartwright (ref 3), and shallow and deep crack limits (ref 1). The objective here is to extend the prior work, based primarily on the new K results of Baratta (ref 4) for this problem, and describe new, more accurate K and load-line displacement, δ, expressions.

An important application for round bar K and δ results is fracture toughness testing of ceramics and other advanced materials, which are becoming more commonly used and are often produced in round bar configuration. Metal components in round bar configuration, such as fasteners, are another application for the results here.

STRESS INTENSITY FACTOR RESULTS

Baratta (ref 4) has recently provided K results for a straight-fronted edge crack in a three-point bend round bar with various ratios of support span-to-diameter, S/D. The interest here is primarily S/D = 4, because it is the configuration used for the ASTM fracture toughness standard (ref 5), as well as other standards around the world. Baratta calculated K for a relatively wide range of crack depth-to-diameter ratios, a/D, using a classic Irwin analysis of Qizhi's (ref 6) recently published slice synthesis compliance results for three-point bend configurations. Baratta's results are compared with those from References 2 and 3 in Figure 1, using a K parameter that includes the functional form of the limit solutions and thereby remains finite and non-zero over the entire range of a/D (ref 1).

Most of Baratta's results are a few percent below those of References 2 and 3, but this is expected based on experience with rectangular bend bars. For rectangular bars, the K for the three-point bend configuration with S/W = 4 is 6 percent below that of the pure bend bar for a/W = 0.5 (ref 7). This is about the same as the difference between Baratta's three-point results and Daoud and Cartwright's pure bend results. The difference in both cases is due to the shear stress, which is present in the three-point configuration and absent in pure bending. See Table 1 for a detailed comparison. Note that the plane-strain relationship was used to determine K from the strain energy release rate, G, results of Daoud and Cartwright, as follows:

$$K_{plane\text{-}strain} = [EG/(1-\upsilon^2)]^{1/2} \quad (1)$$

where E is elastic modulus and υ is Poisson's ratio.

There is another set of results in the literature for a pure bend round bar with a straight edge crack, that of Ng and Fenner (ref 8). They used a three-dimensional finite element analysis and reported K for a few points along the crack front, from which an approximate average K can be calculated. For a/D = 0.5, the average normalized K value, $KD^{3/2}/P$, is 14.7, which is in reasonable agreement with Daoud and Cartwright's result in Table 1.

The similar trends of round and rectangular bar results shown in Table 1, as well as the agreement with other data mentioned above, indicate that the Baratta results and the Daoud and Cartwright results could be used to develop K expressions for the round bar.

First, a K expression was developed for three-point bending by using Baratta's results and the shallow crack and deep crack limits from earlier work (ref 1). Using polynomial regression, the K expression for a three-point bend round bar with $S/D = 4$ and a straight-fronted edge crack with $0 \leq a/D \leq 1$, is

$$(KD^{5/2}/PS)(1-a/D)^2/(a/D)^{1/2} =$$

$$3.75 - 9.87(a/D) + 13.97(a/D)^2 - 9.53(a/D)^3 + 2.18(a/D)^4 \tag{2}$$

The left side of Equation (2) is the K parameter including the forms of the limit solution, and the right side is the fitted polynomial. Equation (2) fits the shallow and deep crack limits and Baratta's results for $0.15 \leq a/D \leq 0.70$ within 0.7 percent. The equation fits Baratta's results for $a/D = 0.05$, 0.10, and 0.75 less well, within 2 to 6 percent agreement, but this is believed to be due to the ever-present problem of determining slope near the ends of a data set. The use of limit solutions alleviates this problem.

Secondly, a K expression was developed for pure bending by using the Daoud and Cartwright results and the shallow and deep crack limits, with a procedure similar to the one above. For the pure bend round bar with a straight-fronted edge crack with $0 \leq a/D \leq 1$

$$(KD^{5/2}/PS)(1-a/D)^2/(a/D)^{1/2} =$$

$$3.75 - 9.10(a/D) + 12.27(a/D)^2 - 8.50(a/D)^3 + 2.08(a/D)^4 \tag{3}$$

where the bending moment is defined here as PS/4. Equation (3) fits the Daoud and Cartwright results for $0.125 \leq a/D \leq 0.500$ within 2.1 percent, and less well outside this range. This expression is not as useful as that for three-point bending, because pure bending is more difficult to attain experimentally. However, it can be used as an approximation for three-point bending with high S/D. For example, note that Bush's results for $S/D = 6.67$ are in close agreement with Equation (3), particularly for mid-depth cracks where experimental compliance results are expected to be most accurate.

Finally, referring again to Table 1, note that Equations (2) and (3) give a close representation of the respective K solutions for $a/D = 0.5$, an important configuration for fracture toughness tests. In addition, they fit the K calculations and limit solutions over the entire range of a/D. The K expressions are believed to be generally useful for various fracture and fatigue tests and for a wide range of materials.

LOAD-LINE DISPLACEMENT RESULTS

Qizhi's results (ref 6) lead directly to an expression for δ, but it is wise to use a displacement parameter that is finite and non-zero at both the shallow and deep crack limits. By doing so, the expression can easily be fitted over the whole range of a/D, including the known limit solutions. The shallow crack limit was written as in prior work for the rectangular bar (ref 9) except the bending and shear displacements for a round bar were used (ref 10), obtaining

$$\lim_{a \to 0}(\delta ED/P)(1-a/W)^{5/2}/(S/D)^2 = 0.424(S/D) + 0.920/(S/D) \tag{4}$$

In Equation (4) on the left is the parameter suitable for both shallow and deep limits; and on the right the 0.424(S/D) term represents bending displacement, while the 0.920/(S/D) is the shear displacement. Note that for large S/D the shear displacement diminishes in importance.

The deep crack limit, based on prior work (ref 11), is as follows:

$$\lim_{a\to W}(\delta ED/P)(1-a/W)^{5/2}/(S/D)^2 = 0.494 \tag{5}$$

The prior expression (ref 11) was $\lim_{a\to W}(\delta ED/P)(1-a/W)^{5/2}/(S/D) = 1.975$, which is equivalent to Equation (5) for $S/D = 4$. However, Equation (5) is believed to be the correct general expression for the deep crack δ limit (ref 4).

Qizhi's slice synthesis δ results for $S/D = 4$ (ref 6) are plotted in Figure 2, using the parameter of Equations (4) and (5). The shallow and deep crack limits from Equations (4) and (5) are also shown and can be seen to be in good agreement with Qizhi's results. A δ expression was fitted to Qizhi's results and the limits using polynomial regression to give δ for the three-point bend round bar with $S/D = 4$ and a straight-fronted edge crack with $0 \le a/D \le 1$. It is

$$(\delta ED/P)(1-a/D)^{5/2}/(S/D)^2 =$$

$$1.921 - 4.083(a/D) + 5.945(a/D)^2 - 3.228(a/D)^3 \tag{6}$$

Equation (6) fits the shallow and deep crack limits within 0.3 percent and Qizhi's results within 1.9 percent.

A second set of δ results is shown in Figure 2, Bush's experimental compliance results for a round bar with $S/D = 6.67$. The quite different δ results are expected because of the significantly different S/D. But it is reassuring to note that these experimental δ results are in good agreement with the shallow and deep crack limit solutions used in obtaining Equation (6).

REFERENCES

1. J.H. Underwood and R.I. Woodward, *Experimental Mechanics*, June 1989, pp. 166-168.

2. A.J. Bush, *Experimental Mechanics*, Vol. 16, 1976, pp. 249-257.

3. O.E.K. Daoud and D.J. Cartwright, *Engineering Fracture Mechanics*, Vol. 19, No. 4, 1984, pp. 701-707.

4. F.I. Baratta, "Wide Range Stress Intensity Factors for a Straight-Fronted Edge Crack in a Three-Point Bend, Round Bar," *International Journal of Fracture*, Vol. 60, 1993, pp. R59-R63.

5. "Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials, E399," *1992 Annual Book of ASTM Standards*, Vol. 03.01, ASTM, Philadelphia, 1992, pp. 506-536.

6. Wang Qizhi, *International Journal of Fracture*, Vol. 57, 1992, pp. R15-R18.

7. J.E. Srawley and B. Gross, *Engineering Fracture Mechanics*, Vol. 4, 1972, pp. 587-589.

8. C.K. Ng and D.N. Fenner, *International Journal of Fracture*, Vol. 36, 1984, pp. 291-303.

9. F.M. Haggag and J.H. Underwood, *International Journal of Fracture*, Vol. 26, 1984, pp. R63-R65.

10. R.J. Roark and W.C. Young, *Formulas for Stress and Strain*, McGraw-Hill, New York, 1975.

11. J.H. Underwood, F.I. Baratta, and J.J. Zalinka, *Experimental Mechanics*, December 1991, pp. 353-359.

Table 1. Comparison of K Results for Round and Rectangular Bend Bars for a/D or a/W = 0.5

Round Bar Results	$KD^{3/2}/P$
3-pt bend; analytical compliance (ref 4); S/D = 4.0	14.14
3-pt bend; Equation (2); S/D = 4.0	14.18
Pure bend; finite element analysis (ref 3)	15.08
Pure bend; Equation (3)	15.10
$(KD^{3/2}/P)_{3\text{-POINT}} / (KD^{1/2}/P)_{PURE} = 0.939$	
Rectangular Bar Results	$KBW^{1/2}/P$
3-pt bend; collocation (ref 7); S/W = 4.0	10.63
Pure bend; collocation (ref 7)	11.26
$(KBW^{1/2}/P)_{3\text{-POINT}} / (KBW^{1/2}/P)_{PURE} = 0.944$	

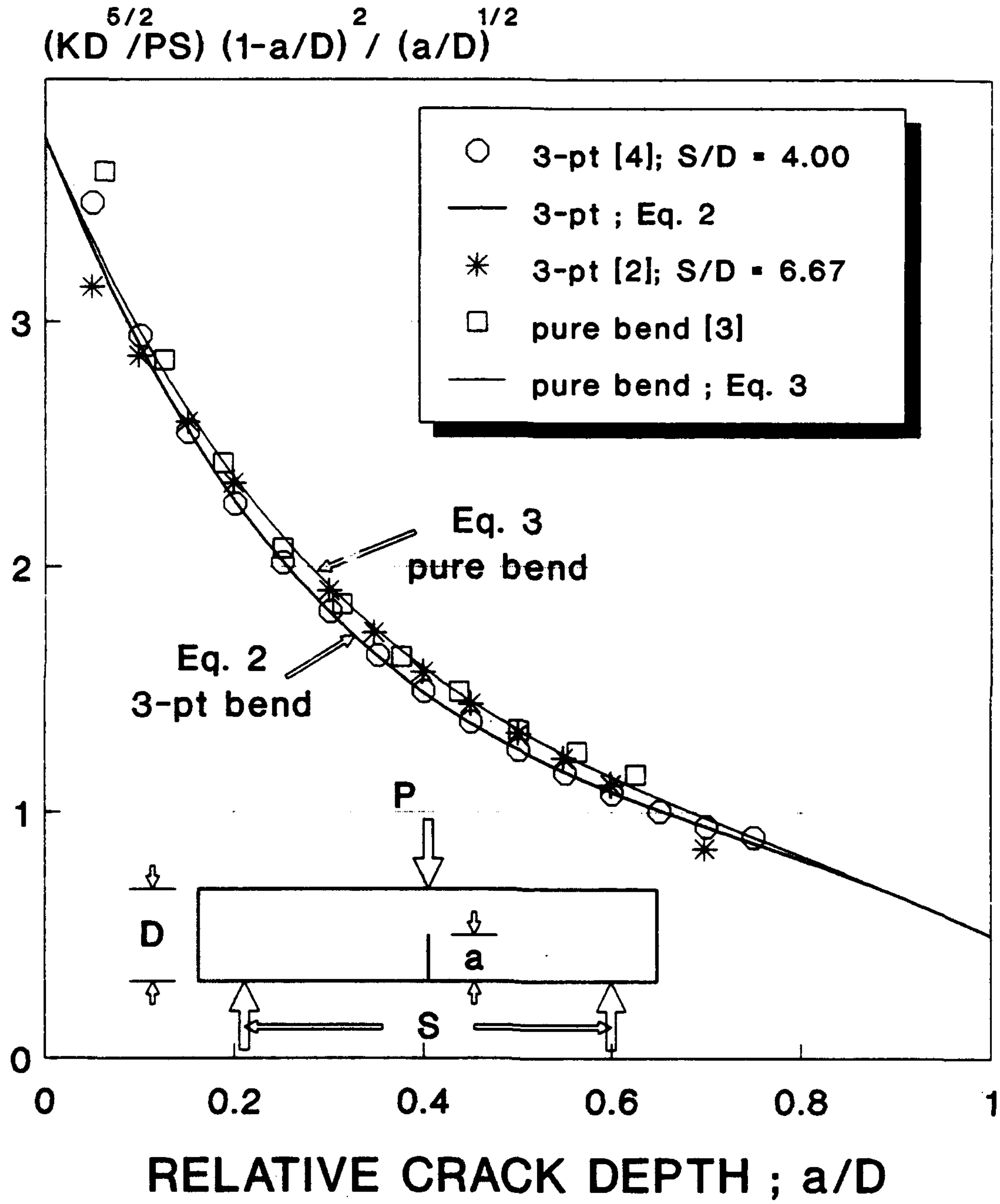

Figure 1. Comparison of K results for round bend bars.

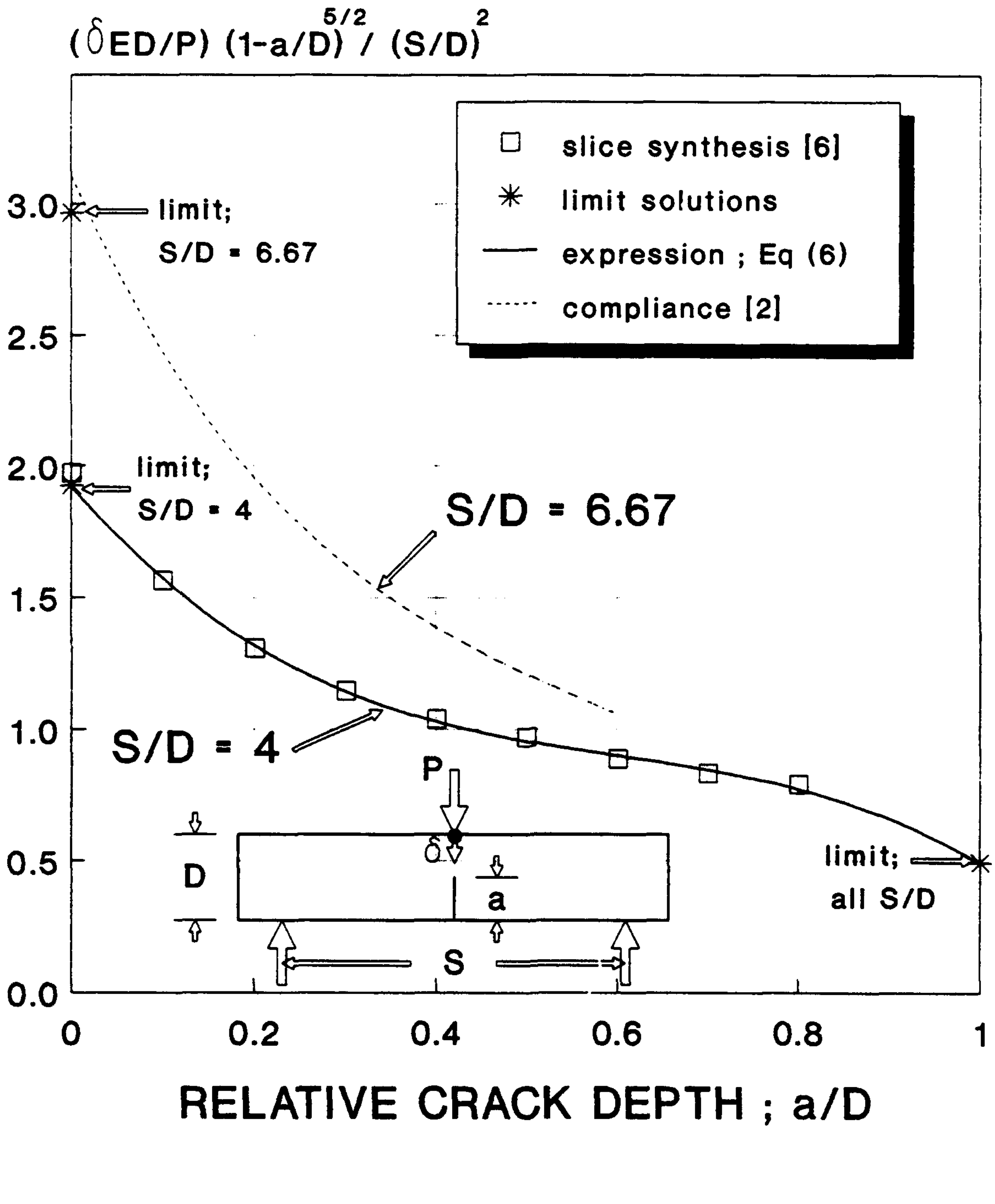

Figure 2. Comparison of δ results for round three-point bend bars.

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